

**An Excess of C IV Absorbers in Luminous QSOs:
Evidence for Gravitational Lensing?**

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ABSTRACT

We have compiled a new and extensive catalog of heavy-element QSO absorption line systems and analyzed the distribution of absorbers in bright and faint QSOs, to search for gravitational lensing of background QSOs by the matter associated with the absorbers. There is a highly significant excess of C IV absorbers in bright QSOs in the redshift range $z = 1.2 - 3.2$, and this excess increases strongly as a function of QSO absolute magnitude. No significant excess is found for Mg II absorbers in the redshift range $z = 0.30 - 1.55$. We rule out several possible reasons for this effect and argue that the C IV excess could be due to gravitational lensing. If so, then the lensing masses must be at $z \gtrsim 1.5$ and within several hundred comoving Mpc of the QSOs, where the C IV absorbers are mainly found. The absence of an excess in the available Mg II sample would then arise because the Mg II data does not sample this region of space.

Subject headings: gravitational lensing — quasars: absorption lines

1. Introduction

One possibly important bias in the study of QSO absorption line systems is that the observed number density of absorbers may be higher than the true number density because of gravitational lensing of the backlighting QSOs. Since there is an observational bias at all redshifts towards QSOs with brighter apparent magnitudes, the current sample of QSOs searched for absorption line systems may contain a large fraction of QSOs observed only because they have been gravitationally brightened beyond some apparent magnitude limit.

Significant lensing mass may be associated with a higher than average density of galaxies and thus a higher than average number of QSO absorbers. This possible association could either be one-to-one, with the lensing mass identified with the absorber (Bartelmann & Loeb 1996), or simply statistical, where the number of absorbers is correlated with the lensing mass. In either case, the geodesics to the QSOs no longer represent random lines-of-sight through the universe with respect to the counts of absorbers.

If this bias were sufficiently strong, the current interpretation of absorption line number statistics would have to be reconsidered. However, it might assist in the search for gravitationally lensed QSOs. For example, lensed QSO candidates could be identified by searching for those QSOs that are both apparently very luminous and have a significant excess of absorption line systems. This bias would also directly affect studies of the QSO luminosity function, since it would be difficult to disentangle the effects of QSO evolution from gravitational lensing without some observational signature of lensing other than luminosity (cf. Pei, 1995).

Several attempts have been made to determine if the lensing bias exists and to assess its importance in studies of absorption line statistics. Thomas and Webster (1990) examined the possibility of lensing by compact objects associated with QSO absorbers for several homogeneous absorber samples. After attempting to fit several lensing models to the absorber

redshift distribution, they concluded that contamination of the samples by absorbers associated with compact lenses is likely to be small for both C IV and Mg II systems; however, lensing associated with some absorbers, especially ones with high equivalent widths, could not be ruled out. Steidel and Sargent (1992) applied the same test to their large homogeneous sample of Mg II absorbers, and concluded that at most a few percent of the QSOs in their sample were observed only because they were brightened by absorbers associated with lensing systems.

Our aim here is not to determine a precise lensing model that may be consistent with the data, but to see if there is any evidence that lens-associated absorption is common. This approach was taken by York et al. (1991, hereafter Y91), who looked at the redshift number density of absorbers in bright versus faint QSO samples in a large heterogeneous collection of heavy-element absorption line systems. They found a factor of two increase in the number of absorbers per unit redshift in the bright sample over the faint sample at high ($z \sim 3$) redshifts, and no excess of absorbers between $0.4 < z < 2$.¹ We re-examine this effect using a new and more extensive sample of absorbers, and we present several other tests which show evidence for lens-associated absorption in this sample.

2. The Absorber Catalog and Selection of the QSO and Absorber Samples

The catalog of QSO absorption line systems contains data on all heavy-element absorption lines in the literature, complete up to October 1994, with some additional entries since then. It is an updated version of the QSOALS catalog of Y91, but is more than twice the

¹We note that there was a computational error in the calculations of the redshift number density of Y91; however, the corrected result of the lensing examination remains essentially unchanged.

size, with over 2200 absorbers listed in 484 QSOs, and is the largest sample of heavy-element absorbers compiled to date. More details on the catalog in general can be found in Y91. We have eliminated 7 QSOs with multiple images that are known or strongly suspected to be gravitationally lensed: 0142-100, 0957+561, 1115+080, 1208+101, 1413+117, 1634+267, and 2345+0007. It is not clear if the addition of these QSOs would, in principle, bias our sample one way or the other. The results in the following sections are virtually unaffected when they are included.

Although the catalog of absorbers is compiled from data taken with a wide variety of telescopes and spectrographs, and taken under a range of observing conditions, for various purposes, the information included is enough, in principle, to construct a homogeneous sample of heavy-element absorption line systems. In particular, we need to know the wavelength limits and equivalent width limits (which take into account signal-to-noise and resolution) for each QSO spectrum, in addition to the redshifts z , equivalent widths W , and line identifications for each absorber. The observed spectral equivalent width limit will generally be a function of wavelength, but the catalog lists only one 1σ estimate for the entire wavelength range of each spectrum. Partly to overcome this deficit, and partly because different authors use different equivalent width criteria for including absorption lines in their lists, a conservative 5σ observed equivalent width limit for each spectrum was used to select absorbers from the catalog.

Selected absorption systems must have been identified with at least three lines, or two lines if they belonged to a doublet, in which case the equivalent width ratio of the intrinsically weaker to stronger doublet member must be less than or equal to 1, within the listed measurement errors. We have concentrated on absorbers containing either C iv 1548Å or Mg II 2796Å, since these are the most commonly identified absorption lines. Since absorbers with these lines are usually seen in different redshift regimes, each ion has been treated

separately in the following analysis. Only a small number of absorbers are observed with both C IV and Mg II lines. We have analyzed several other lines identified in relatively large numbers including Si II 1527Å, which will be discussed in the context of the C IV and Mg II results in Section 4. We note that there are only 42 (out of 655) reliably identified absorbers in the catalog in which C IV or Mg II was not detected even though their lines would have fallen into the observed spectral range.

The Ly α forest region of each spectrum has been excluded, since it is generally very difficult to unambiguously distinguish lines of heavy-element ions from the more numerous Ly α lines. The entire spectral range within 5000 km/s of the QSO emission and the absorbers identified there have been excluded, as is commonly done, since there may be a direct association between the QSOs and the absorbers in that region (Aldcroft, Bechtold, & Elvis, 1994). QSO spectra with very poor (> 400 km/s) and very good (< 35 km/s) velocity resolution have also been eliminated to avoid blending of distinct absorbers in the former case, and to avoid splitting single absorbers into multiple components in the latter case, either of which could distort the counts of absorbers. After these selection criteria were applied to the catalog, 398 C IV and 257 Mg II absorbers remained. In the following analysis, we have not combined absorbers that may originate in the same galaxy ($\Delta v \lesssim 500$ km/s), but doing so does not significantly affect the results.

3. Analysis of the QSO and Absorber Samples

We now examine correlations of absorber properties with estimated QSO luminosity. We find no significant correlations, in either the C IV or Mg II absorber samples, between QSO absolute magnitude, M_V , and either absorber redshift, absorber equivalent width, observed spectral equivalent width limit, or spectral resolution, except possibly at the extreme ends of the QSO absolute magnitude distribution which have been excluded as described below.

Our first test for lensing associated with absorbers is to compare the redshift number density of absorbers, $d\mathcal{N}/dz$, in “bright” and “faint” samples of QSOs, similar to the lensing test described in Y91. Although the sample of QSOs, spectra, and absorbers has been selected with a set of uniformly applied criteria, an estimate of $d\mathcal{N}/dz$ must take into account the remaining variations in wavelength ranges, observed equivalent width limits, and absorber rest equivalent widths. To do this, we have used the following weighting scheme for the absorbers.

Each detected absorption line occupies a point in the z - W plane, and each QSO spectrum samples some z and W region in that plane according to the selection criteria referred to above. The density of absorbers per QSO, $\partial^2\mathcal{N}/\partial z\partial W$, is a series of delta functions centered at each (z, W) absorber point, weighted by the reciprocal of S_a , the number of QSO spectra in which an absorber *could* have been detected in both z and W ,

$$\partial^2\mathcal{N}/\partial z\partial W = \sum_a S_a^{-1} \delta(W - W_a) \delta(z - z_a). \quad (1)$$

The average number of absorbers per QSO, \mathcal{N} , in some redshift and equivalent width region is the integral of $\partial^2\mathcal{N}/\partial z\partial W$, which is just the sum of the weights in that region. Then in the ranges Δz and ΔW , the average redshift number density will be $d\mathcal{N}/dz = \mathcal{N}/\Delta z$, and the average equivalent width number density will be $d\mathcal{N}/dW = \mathcal{N}/\Delta W$.

Cuts in equivalent width and redshift are only necessary in regions that are poorly sampled, i.e., where S_a is small. The well-sampled regions of the z - W plane for C IV and Mg II are bounded by the limits shown in Figures 1 and 2. Mg II absorption has often been observed at higher redshifts, but the high- z cutoff has been set to $z = 1.55$ because telluric absorption and night sky emission lines can reduce the reliability of Mg II detections beyond that point.

The QSOs have been divided into bright and faint samples in two ways. First, the median value of the QSO absolute visual magnitude distribution (assuming $q_o = 1/2$, $H_o =$

$100h \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $\alpha = 0.7$ (Veron-C  t   & Veron 1991)) was used as the dividing point for the bright and faint QSOs, after cuts in M_V (seen as the limits in Figure 4) were made to ensure adequate sampling of z and W . The sample division is nearly independent of q_o . Second, we fit a line through a plot of QSO redshift versus apparent visual magnitude, so that at each redshift there are roughly equal numbers of QSOs above and below the line. Here, both QSO luminosity evolution, and any selection effects where more luminous QSOs are selected at higher redshifts, are taken into account by defining a bright and faint sample at each redshift. We have found that the two methods divide the QSO samples roughly the same way, except at the lower redshifts where the slope in the M_V distribution versus redshift is fairly steep, resulting in more QSOs in the faint half of the M_V division at lower redshifts. The results for both methods are presented here.

Figure 1 shows Mg II and C IV $d\mathcal{N}/dz$ versus redshift for the bright and faint QSO samples. The solid histograms show the average $d\mathcal{N}/dz$ for 100 randomly selected QSO samples of the same sizes as the real samples, and the 1σ deviations in those samples are shown by the dashed histograms. Figure 1 clearly shows that bright QSOs in the C IV sample have more absorbers per unit redshift than the faint sample, and that this seems to be true at all the observed redshifts. The probability that the observed C IV $d\mathcal{N}/dz$ difference in the bright and faint samples is the result of chance is 7.4×10^{-6} for the division of QSOs by M_V , and 6.0×10^{-11} for the line fit division. There is no significant difference, however, between the bright and faint halves of the Mg II sample (probabilities 0.16 and 7.9×10^{-2} for the respective divisions).

The difference seen in the C IV sample is *not* due to a higher density of small equivalent width systems in the bright QSO sample. Fig. 2 shows $d\mathcal{N}/dW$ versus absorber equivalent width. While the *amplitude* of $d\mathcal{N}/dW$ is higher for the bright C IV sample than for the faint (as expected from the $d\mathcal{N}/dz$ result), the *shapes* of the $d\mathcal{N}/dW$ distributions are virtually

the same. The excess occurs at *all* values of W . Thus the absorbers in both the bright and faint QSO samples seem to have identical equivalent width properties, except that there are more absorbers in the bright sample. Figure 2 shows that the Mg II absorbers also have a similar equivalent width distribution in the bright and faint halves, but as expected from the Mg II $d\mathcal{N}/dz$, the amplitudes of both $d\mathcal{N}/dW$ distributions are about the same.

Systematic differences between observers in defining signal-to-noise in their spectra, combined with an uneven distribution of bright and faint QSOs among the observers for the C IV sample only, do not explain the noted effects. We show in Fig. 3 the C IV $d\mathcal{N}/dz$ and $d\mathcal{N}/dW$ distributions in bright and faint QSO samples (using the median M_V as the dividing point) for the single largest homogeneous C IV sample (Sargent, Boksenberg, & Steidel 1988; Steidel 1990) which includes 144 absorbers in 57 QSOs which have available visual magnitude estimates. These samples include the “complete sample” of systems with $W \geq 0.15\text{\AA}$ described in Steidel (1990), excluding those systems within 5000 km/s of the QSO emission. As in Fig. 1, the value of $d\mathcal{N}/dz$ in the brighter half is always higher than in the fainter half. The probability of the observed difference occurring by chance is 6.6×10^{-4} . The slopes of the $d\mathcal{N}/dW$ distributions in Fig. 3 are almost identical, while the amplitudes differ by a nearly fixed amount, as is the case with the C IV distributions in Fig. 2. Thus the homogeneous sample shows the same behavior as the full sample, and inhomogeneity is not the cause of the observed C IV excess.

A second test for lensing is to compare the number of absorbers seen at each QSO absolute magnitude with the average number that would be expected at that magnitude. If lens-associated absorption occurs, we expect to find more absorbers on average in the spectra of more luminous QSOs, because the fraction of lensed QSOs should increase as a function of luminosity. The average number of absorbers expected in a QSO, \mathcal{N} , can be found by summing the weights in equation 1 that lie in the region of the z - W plane covered by the

QSO spectrum. Fig. 4 shows the total number of absorbers observed \mathcal{N}_{obs} , divided by the average expected total number of absorbers \mathcal{N}_{ave} , for each M_V bin. There is a dramatically strong correlation ($Q(\chi^2) = 4 \times 10^{-4}$) between the number of absorbers and M_V for the C IV sample, while there is no significant trend in the Mg II data. The absence of a correlation in the Mg II data supports the argument that the C IV results are not due to any selection effects since both samples come from the same QSO spectra and were analyzed in precisely the same way. Both of the results in Fig. 4 are consistent with the $d\mathcal{N}/dz$ distributions for the bright and faint QSO samples. For the homogeneous C IV sample described above, the results are consistent with Fig. 4 but are less significant owing to the smaller QSO sample size.

4. Discussion

We find clear evidence for an excess of C IV absorbers in bright QSOs. We have allowed for differences among the various data sets in the catalog by carefully comparing equivalent width detection limits, resolution, and observable redshift limits. For reasons discussed above, we find it improbable that selection effects are causing the observed results. First, the effect occurs at all values of W , and is not due to higher spectral sensitivity achievable in brighter QSOs. Second, the Mg II data at low z and the C IV data at high z come from many of the same QSO spectra. If observers systematically overestimated or underestimated the signal-to-noise ratios, the effect should show up in both Mg II and C IV, which it does not. Finally, the largest homogeneous sample within our full sample shows the same effect observed in the full sample, despite the smaller range in M_V and the smaller total sample size.

Could the effect be intrinsic to the QSOs? The radiation fields near QSOs are thought to affect the ionization state and reduce the counts of the nearby absorbers (Ellingson et al.

1994). However, this effect is opposite to the correlation between C IV absorber counts and M_V seen here. In the results above, we have excluded the regions within 5000 km/s of the QSOs, and the results do not change significantly when regions up to 20000 km/s from the QSOs are excluded. Unless ejection velocities of absorbers from QSOs often exceed several tens of thousands of km/s *and* narrow line profiles are maintained, our results are unlikely to be due to an effect intrinsic to QSOs. Furthermore, an ejection related explanation would have to involve an excess of absorbers related to luminosity and a luminosity independent intergalactic sample of absorbers. To explain the identical dN/dW slopes in Fig. 2 for C IV, the ejected sample and the intergalactic sample would have to have virtually identical distributions of dN/dW . This possibility seems unlikely, given the different physical origins. Finally, some ionization effect would be expected, for which we find no evidence in our discussion of Si II data below.

A final possibility remains, namely that mass indirectly associated with the C IV absorbers brightens the QSOs through gravitational lensing. However, the lensing is probably not of the kind that produces multiple QSO images for two reasons. First, the HST QSO Snapshot survey (Maoz et al. 1993) and numerous ground-based optical and radio surveys for multiply-imaged QSOs (e.g. Jaunsen et al. 1995) have shown that the fraction of bright QSOs with resolved multiple images within several arcseconds is much less than 1%. For multi-image lensing to explain our results, the image splittings would have to be either less than the resolution of these surveys or so much greater that their identifications have been overlooked. Clusters are able to produce multiple QSO images with several arcminute separations, but only for fairly specific mass configurations (Paczynski & Gorski 1981) which are probably not common enough (Turner, Ostriker, & Gott 1984) to explain the amplitude of our results. Second, the probability density for encountering lenses producing multiple images is quite small near the QSOs (Turner, Ostriker, & Gott 1984). Figure 5 shows the region of space sampled by the catalog used here by showing the distances of the absorbers

and the distances of the background QSOs. Various selection criteria discussed earlier are delimited by dashed lines. Any lenses in our sample must be at a redshift $z \gtrsim 1.5$ and within several hundred comoving Mpc of the QSOs to be associated with detected C IV absorbers. Impact parameters through clusters of galaxies do not have to be restricted to those that produce multiple images in order to have significant amplification, and as the QSO-lens distance becomes smaller, the probability of producing only a single image increases (as can be seen in Figure 6 of Young et al. 1980). If the probability density for this type of lensing is greatest within a few hundred Mpc of a QSO, we would not expect a significant correlation between Mg II absorber counts and QSO luminosity, since most of the Mg II absorbers are found much farther away from their QSOs (Figure 5). Unfortunately the sample of Mg II absorbers within a few hundred Mpc of their QSOs is still too small to see if their numbers are correlated with QSO luminosity.

Differences between the lensing signatures of Mg II and C IV could also arise if there is a segregation of absorber ions in how they trace lensing potentials, or in how the ionization environments differ near the QSO compared with the average over all space. We have analyzed the Si II 1527Å (rest wavelength) absorbers which have ionization properties similar to Mg II, but are found in the space regime (Fig. 5) of C IV (rest wavelengths 1548Å, 1550Å). The counts versus M_V distribution of Si II, shown in Figure 4, is more similar to that of C IV, than of Mg II. The χ^2 probability that $\mathcal{N}_{obs}/\mathcal{N}_{exp}$ vs. M_V distribution for Si II is consistent with that for Mg II is 0.43 while the probability is 0.94 for C IV. This result is consistent with the idea that the lack of a count/luminosity correlation in the Mg II sample is due to a reduced probability of intercepting a lens far away from a QSO, rather than to, say, an ionization effect in QSO ejecta that leaves C IV but eliminates Mg II, or to some effect of segregation of C IV, Mg II, and Si II near the QSO.

It will be important to obtain samples in a given absorber species over the largest

redshift range possible, either by extending the redshift range for C IV, Si II, Si IV, Al II, and O I to lower redshifts by deblending the listed lines from the Ly α forest (Kulkarni et al. 1996), or deblending features from telluric absorption and atmospheric emission at long wavelengths to obtain higher redshift samples of Mg II (Caulet 1989). Large homogeneous QSO and absorber surveys, such as the Sloan Digital Sky Survey, are being planned, which should increase the total QSO and absorber samples at all redshifts by a factor exceeding 100. Another survey is under way to obtain a large number of absorbers in a several complete samples of selectively faint QSOs (Borra et al. 1996). We expect that the mean C IV $d\mathcal{N}/dz$ in this sample will be significantly lower than the average $d\mathcal{N}/dz$ in Fig. 1.

Further work will also be needed to see if detailed lensing models are consistent with our results.

5. Conclusions

The published sample of intervening C IV absorbers in QSO spectra shows a strong luminosity dependent number density excess compared to the published Mg II absorber sample. Systematic selection effects in the data have been tested for by searching for differences in the absorber equivalent width distributions in intrinsically bright and faint QSO samples, and by checking that the effect appears in the largest homogeneous sample within our heterogeneous but carefully treated sample from the literature. No explanation of this sort was found. While we do not believe that the effect shown here is due to a selection bias, such as overestimating the equivalent width detection limit for faint QSOs relative to bright ones, if it were, then all existing sample of QSO absorbers are subject to this effect, and all work on $d\mathcal{N}/dz$ for CIV must be reconsidered in light of this bias. The reduced catalog we used is available on line from DEVB, so these types of effects can be examined by others.

Furthermore, no evidence was found that more luminous QSOs have gas with very high ejection velocities, though it cannot be ruled out entirely. Since we undertook this study to search for a lensing bias in the counts of QSO absorbers, we briefly explored the types of lensing that might be relevant. Various observational selection effects allow the C IV absorbers to sample only the space at $z \gtrsim 1.5$ and within 400 Mpc of the background QSOs, whereas the Mg II data set does not sample this region. Therefore, relevant lensing must occur at $z \gtrsim 1.5$ and within 400 Mpc of the QSOs. It must consist of amplification without multiple images, as the latter are not seen in the vast majority of QSOs.

Several observational tests were mentioned that may shed light on the cause of the C IV excess in more luminous QSOs. These involve achievable increases in sample size and in redshift coverage for the Mg II and C IV samples.

The effect, no matter what the cause, is so strong that $d\mathcal{N}/dz$ – an important statistic for inferring morphology of the absorbers – must be considered uncertain until the effect is understood.

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Fig. 1.— The redshift number density of absorbers for Mg II ($0.3 < z < 1.55$) and C IV ($1.2 < z < 3.2$), in bright (filled symbols) and faint (open symbols) QSOs. Squares show the QSO division by the median absolute magnitude, M_V , and triangles show the division by a line fit to apparent magnitude versus redshift. The histograms show the average dN/dz and 1σ deviation for 100 Monte Carlo simulations.

Fig. 2.— The rest equivalent width number density of absorbers for C IV and Mg II. Filled squares show the results for bright QSOs, and open squares for faint QSOs, separated by their median M_V .

Fig. 3.— The C IV redshift number density (top) and equivalent width number density (bottom) for bright (filled squares) and faint (open squares) QSOs in the homogeneous sample of Sargent, Boksenberg, & Steidel (1988), and Steidel (1990). The histograms in the top plot are as in Fig. 1. Only absorbers with $1.2 < z < 3.2$ and $W > 0.15\text{\AA}$ (5σ) have been used. Absorbers lying within 150 km/s have been combined (as in Steidel 1990) for the dN/dz plot.

Fig. 4.— The ratio of the number of observed absorbers \mathcal{N}_{obs} , to the number of absorbers expected on average \mathcal{N}_{ave} , as a function of QSO absolute magnitude. There is a strong increasing trend in the C IV sample (filled squares), while there is no significant trend in the Mg II sample (filled circles). The Si II sample (open squares) also shows an increasing trend.

Fig. 5.— The comoving distances to the QSOs and absorbers in the C IV and Mg II samples. The regions inside the dashed lines are bounded by the atmospheric redshift limits and Ly α forest cutoff for each absorber ion, and show where the absorbers could have been detected.

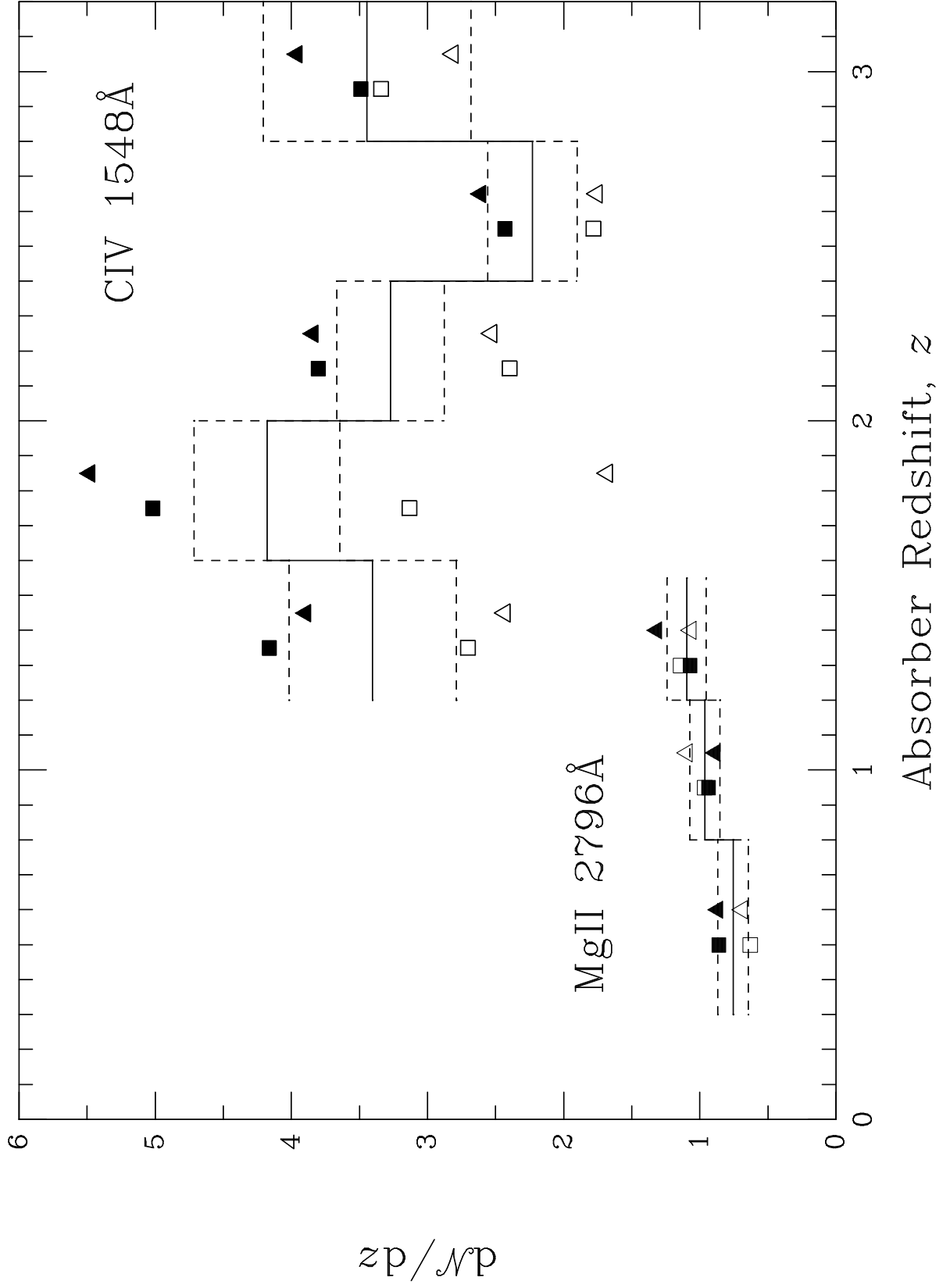


Fig. 1.—

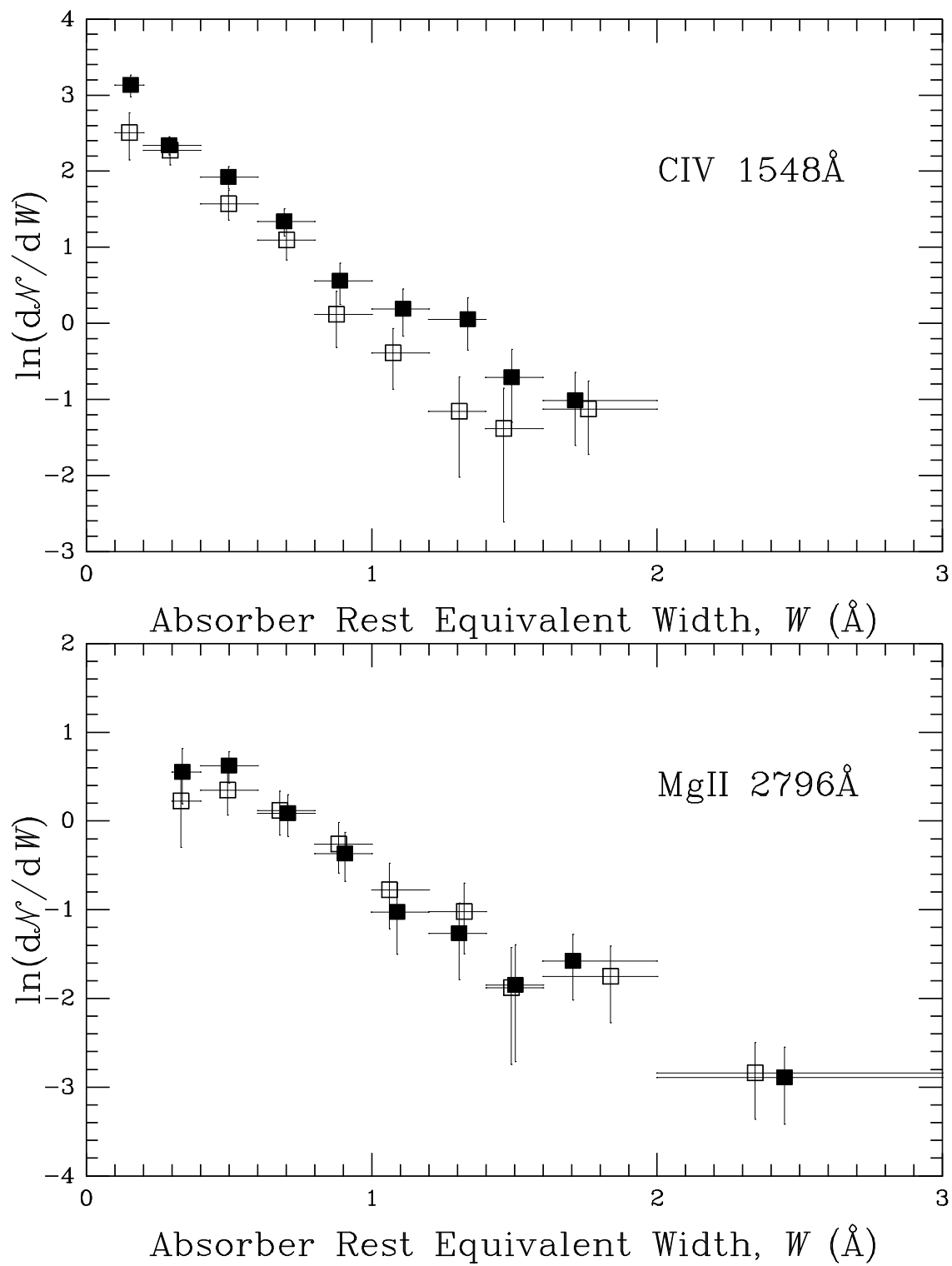


Fig. 2.—

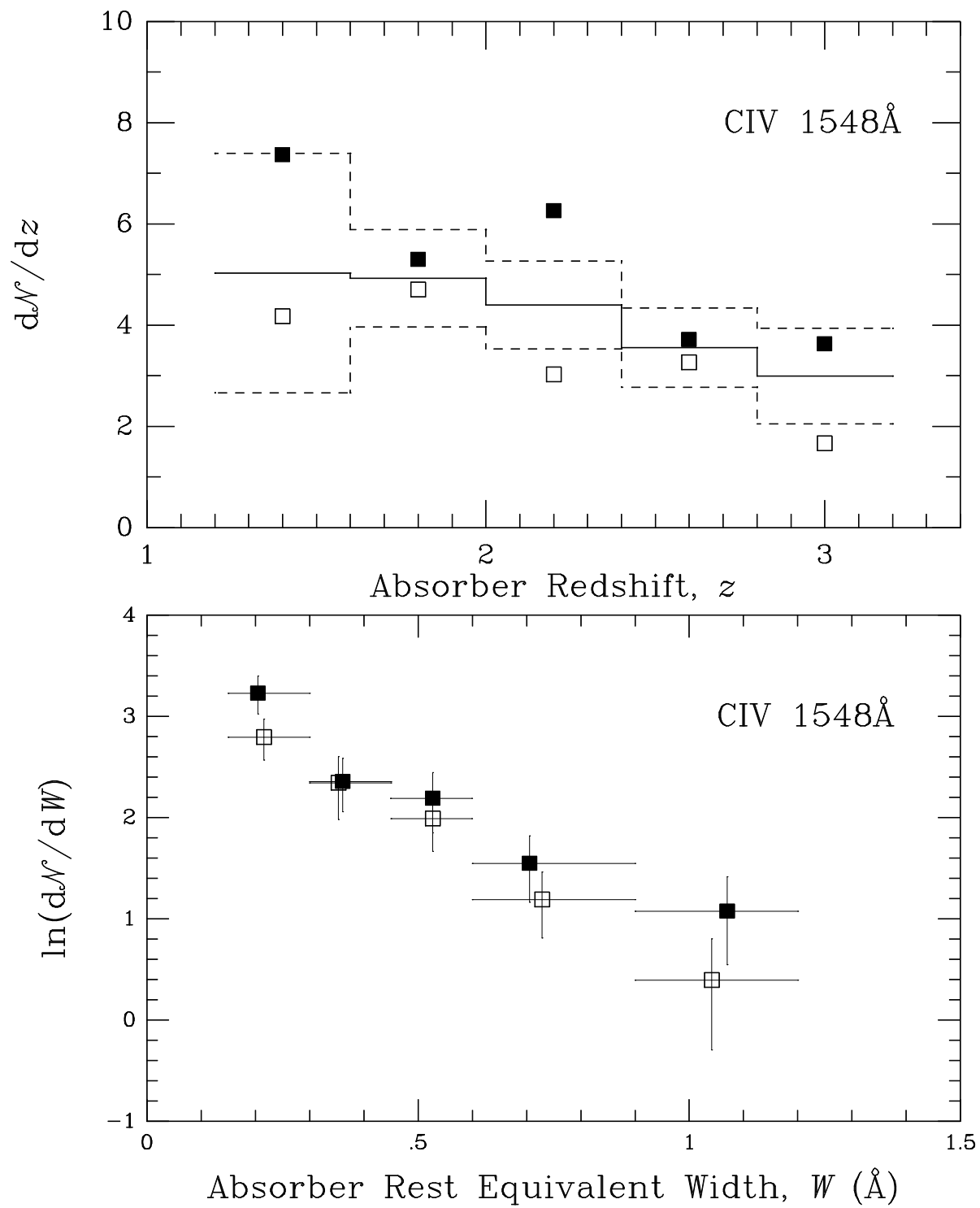


Fig. 3.—

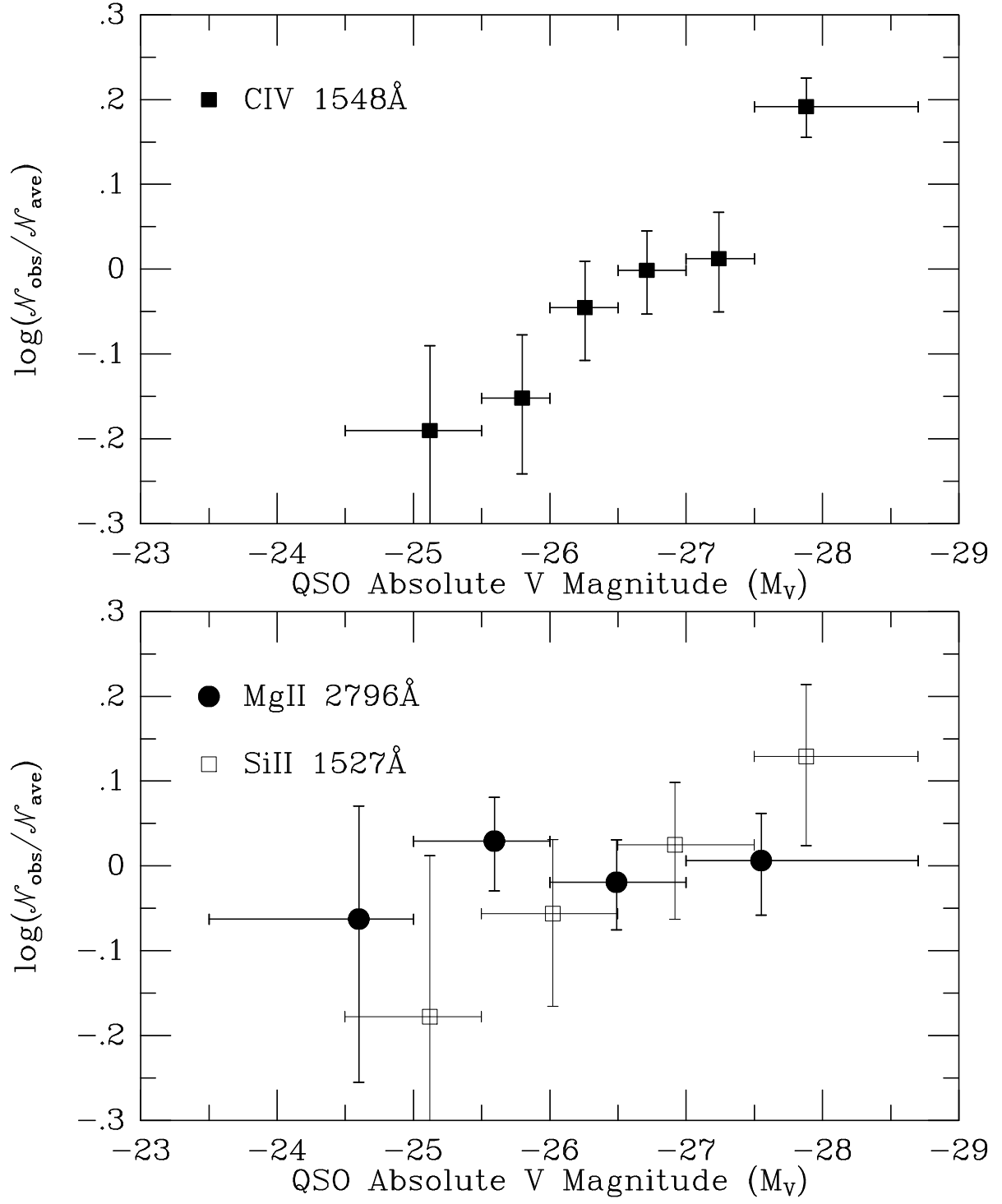


Fig. 4.—

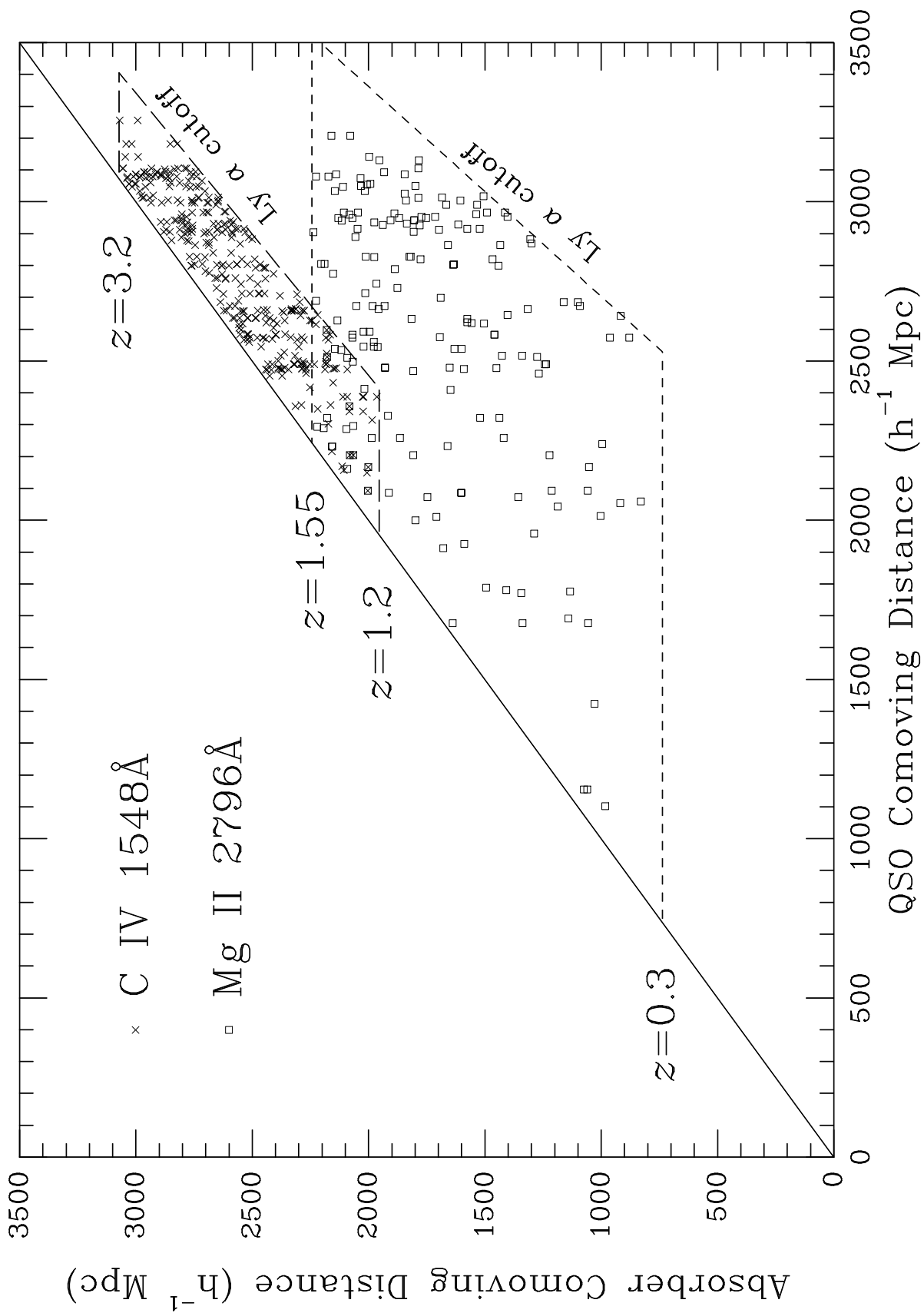


Fig. 5.—